GDR dissipation and nuclear shape in hot fast-rotating Dy nuclei

van Schagen, JPS; Alhassid, Y; Bacelar, JC; Bush, B; Harakeh, MN; Hesselink, WHA; Hofmann, HJ; Kalantar-Nayestanaki, N; Noorman, RF; Plompen, AJM

Published in:
Physics Letters B

DOI:
10.1016/0370-2693(93)91277-T

Physics Letters B 308 (1993) 231–236
North-Holland

PHYSICS LETTERS B

GDR dissipation and nuclear shape in hot fast-rotating Dy nuclei

J.P.S. van Schagen [a], Y. Alhassid [b], J.C. Bacelar [c], B. Bush [d], M.N. Harakeh [a], W.H.A. Hesselink [a], H.J. Hofmann [c], N. Kalantar-Nayestanaki [a], R.F. Noorman [c], A.J.M. Plompen [a], A. Stolk [a], Z. Sujkowski [a,c,e] and A. van der Woude [c]

[a] *Faculteit Natuurkunde en Sterrenkunde, Vrije Universiteit, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[b] *Center for Theoretical Physics, Sloane Physics Laboratory and Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06511, USA*
[c] *Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands*
[d] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[e] *Soltan Institute for Nuclear Studies, PL 05-400 Swierk, Poland*

Received 3 March 1993
Editor: J.P. Schiffer

The statistical γ-ray decay of the GDR built on excited states in Dy nuclei has been investigated for selected domains of angular momentum up to about $70\hbar$ and temperatures in the range 1–2 MeV. The GDR strength distributions extracted from the data indicate large average nuclear deformations ($\beta \sim 0.35$) at high angular momentum and average temperatures $T \geqslant 1.5$ MeV. This experimental observation is supported by results from calculations in which thermal shape fluctuations are taken into account around an oblate equilibrium deformation β_{eq}. Although this equilibrium deformation increases with angular momentum, the calculations show rather large and constant average deformations $\langle \beta \rangle \sim 0.35$.

The statistical γ-ray decay of the giant dipole resonance built on excited states is an interesting probe to study the evolution of the nuclear shape at finite temperature ($T = 1$–2 MeV) and large angular momentum [1]. In analogy to the GDR built on the ground state, the strength distribution of the GDR built on excited states is expected to reflect the deformation of the states upon which the GDR is built. However, the statistical γ-ray decay of a compound nucleus formed in a fusion–evaporation reaction can occur at each decay step. The nuclear deformation is thus probed for an ensemble of nuclear states at different excitation energies or temperature and a wide range in angular momentum.

To restrict the range in angular momentum of the states upon which the GDR is built, the γ-ray multiplicity and the total summed energy of the γ-rays emitted in the decay can be used [1–3]. In the study of the angular-momentum dependence of the GDR built on highly excited states in ^{156}Dy by Bruce et al. [4] and Stolk et al. [5] this technique has also been employed. Both studies report large widths, 2–3 times the width for the GDR built on the ground state, and suggest a change of nuclear deformation with increasing angular momentum.

Recently, a theoretical scheme has been developed in which shape transitions, and their effect on the spectral shapes of giant resonances, can be calculated [6–10]. In these calculations the thermal shape fluctuations are properly taken into account. Comparison with experimental data for ^{160}Er* and ^{166}Er* [11–13] and ^{90}Zr* and ^{92}Mo* [14,15] have shown that these calculations can explain the data, which involve angular momenta up to an average value $\langle J \rangle = 33\hbar$, very well.

In this letter we report on the results of a study of the GDR in the decay of ^{156}Dy* in which a selection on angular momentum has been performed at high temperature ($T \sim 1.5$–2 MeV). Comparison of the experimental results with calculations, performed in the framework of Landau shape transitions and statistical shape fluctuations, shows that the theory can account for the observed large widths well. It is further found that the equilibrium deformation, around

Physics Letters B 308 (1993) 231-236
North-Holland

PHYSICS LETTERS B

GDR dissipation and nuclear shape in hot fast-rotating Dy nuclei

J.P.S. van Schagen [a], Y. Alhassid [b], J.C. Bacelar [c], B. Bush [d], M.N. Harakeh [a], W.H.A. Hesselink [a], H.J. Hofmann [c], N. Kalantar-Nayestanaki [a], R.F. Noorman [c], A.J.M. Plompen [a], A. Stolk [a], Z. Sujkowski [a,c,e] and A. van der Woude [c]

[a] *Faculteit Natuurkunde en Sterrenkunde, Vrije Universiteit, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[b] *Center for Theoretical Physics, Sloane Physics Laboratory and Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06511, USA*
[c] *Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands*
[d] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[e] *Soltan Institute for Nuclear Studies, PL 05-400 Swierk, Poland*

Received 3 March 1993
Editor: J.P. Schiffer

The statistical γ-ray decay of the GDR built on excited states in Dy nuclei has been investigated for selected domains of angular momentum up to about $70\hbar$ and temperatures in the range 1–2 MeV. The GDR strength distributions extracted from the data indicate large average nuclear deformations ($\beta \sim 0.35$) at high angular momentum and average temperatures $T \geqslant 1.5$ MeV. This experimental observation is supported by results from calculations in which thermal shape fluctuations are taken into account around an oblate equilibrium deformation β_{eq}. Although this equilibrium deformation increases with angular momentum, the calculations show rather large and constant average deformations $\langle \beta \rangle \sim 0.35$.

The statistical γ-ray decay of the giant dipole resonance built on excited states is an interesting probe to study the evolution of the nuclear shape at finite temperature ($T = 1$–2 MeV) and large angular momentum [1]. In analogy to the GDR built on the ground state, the strength distribution of the GDR built on excited states is expected to reflect the deformation of the states upon which the GDR is built. However, the statistical γ-ray decay of a compound nucleus formed in a fusion–evaporation reaction can occur at each decay step. The nuclear deformation is thus probed for an ensemble of nuclear states at different excitation energies or temperature and a wide range in angular momentum.

To restrict the range in angular momentum of the states upon which the GDR is built, the γ-ray multiplicity and the total summed energy of the γ-rays emitted in the decay can be used [1–3]. In the study of the angular-momentum dependence of the GDR built on highly excited states in ^{156}Dy by Bruce et al. [4] and Stolk et al. [5] this technique has also been employed. Both studies report large widths, 2–3 times the width for the GDR built on the ground state, and suggest a change of nuclear deformation with increasing angular momentum.

Recently, a theoretical scheme has been developed in which shape transitions, and their effect on the spectral shapes of giant resonances, can be calculated [6–10]. In these calculations the thermal shape fluctuations are properly taken into account. Comparison with experimental data for ^{160}Er* and ^{166}Er* [11–13] and ^{90}Zr* and ^{92}Mo* [14,15] have shown that these calculations can explain the data, which involve angular momenta up to an average value $\langle J \rangle = 33\hbar$, very well.

In this letter we report on the results of a study of the GDR in the decay of ^{156}Dy* in which a selection on angular momentum has been performed at high temperature ($T \sim 1.5$–2 MeV). Comparison of the experimental results with calculations, performed in the framework of Landau shape transitions and statistical shape fluctuations, shows that the theory can account for the observed large widths well. It is further found that the equilibrium deformation, around

0370-2693/93/$ 06.00

which the shape fluctuations are taken, increases significantly with increasing angular momentum (see table 2), but that this effect is largely masked by the shape fluctuations leading to a rather stable $\langle \beta \rangle$ which is consistent with the experimental data.

The measurements were performed with the AVF cyclotron facility of the Kernfysisch Versneller Instituut in Groningen. A 1.0 mg/cm^2 thick, 95% enriched ^{116}Cd target was bombarded with 200 MeV $^{40}Ar^{8+}$ ions. The effective interaction energy was 196 MeV. The ^{156}Dy* compound nuclei were formed with $E^* = 92.5$ MeV and a range in angular momentum of up to $90\hbar$. The experimental set-up was the same as the one used in the study of ref. [3]. The high-energy γ-rays from GDR decay were detected in a large $10'' \times 14''$ NaI detector provided with a plastic anticoincidence shield. The total γ-ray energy and the γ-ray multiplicity were measured with a sum spectrometer consisting of six NaI segments and a multiplicity filter consisting of eight NaI detectors. This allowed the selection of GDR decay for angular-momentum windows with different average angular momenta $\langle J \rangle$. Contrary to the experiment of ref. [5] the beam and the recoiling nuclei were stopped in a catcher foil 26 cm downstream of the target. The experimental details are given elsewhere [16].

Three spectra measured for the statistical decay of the GDR in the compound nucleus ^{156}Dy* are shown in fig. 1. The spectra correspond to three angular-momentum windows with average angular momenta of $\langle J \rangle = 32\hbar$, $46\hbar$ and $62\hbar$. To determine the GDR strength distribution, spectra calculated within the statistical model using the modified computer code CASCADE [17] have been fitted to the experimental data. The population cross sections as a function of J for the different angular-momentum windows in ^{156}Dy* were deduced from the total fusion cross section taken in accordance with the systematics of ref. [18]. These cross sections were averaged over the beam energy across the target and folded with the angular-momentum acceptance of each window. The angular-momentum acceptances have been determined from the fold distributions and the geometry of the setup in a Monte Carlo procedure [5,19]. More details on this procedure can be found in ref. [16]. The resulting full width at half maximum for each of the three angular-momentum windows is about $20\hbar$.

The present data have been normalized to CAS-

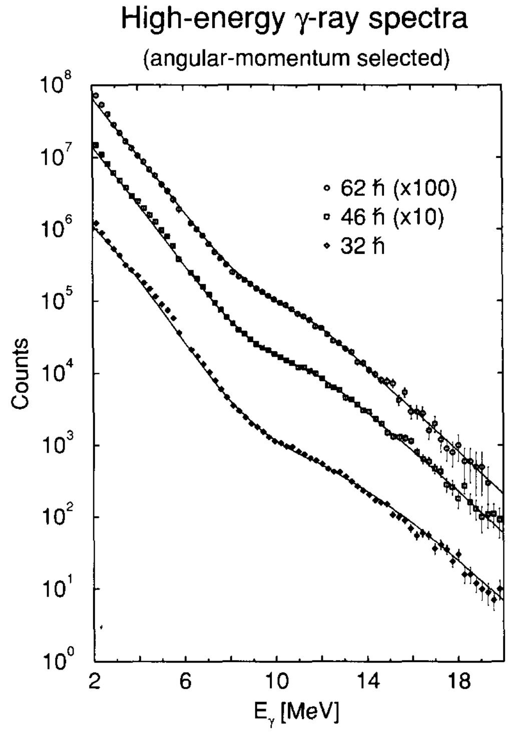

Fig. 1. High-energy γ-ray spectra for different angular-momentum domains obtained by gating on different multiplicities and sum-energies. The curves through the data are discussed in the text.

CADE calculations in a restricted region $E_\gamma = 2.5$–6 MeV. In the region the γ-ray yield is independent from the initially assumed GDR parameters. The GDR parameters of the double-lorentzian strength distribution were then deduced from a fit of the calculated spectra folded with the detector response function to the experimental data in the range $E_\gamma = 8.5$–21 MeV. In total four parameters were fitted: the energies of both components E_1 and E_2, the strength in the first component S_1 and the width parameter C assuming that the widths depend on the energy as $\Gamma_i = CE_i^2$, in accordance with the systematics of the experimental data for the ground-state GDR as evaluated by Carlos et al. [20]. The TRK sum rule was assumed to be exhausted, i.e. $S_1 + S_2 = 1$. The fits have been performed for two level-density parameters, $a = A/8$ MeV^{-1} and $a = A/9$ MeV^{-1}. In both cases a good description of the experimental data was obtained over the whole energy range but especially in the region of the GDR as can be seen from the solid curves through

Table 1
The GDR parameters for ^{156}Dy resulting from the best fits. The quoted errors have been obtained by adding the systematic and statistical errors.

$\langle J \rangle$ ($\hbar$)	E_1/E_2	S_1/S_2	$\langle E \rangle$ (MeV)	β	C ($\times 10^{-2}$) (MeV^{-1})	χ^2/N
32	0.84 ± 0.07	2.33 ± 0.05	15.2 ± 0.3	-0.20 [a] ± 0.06	4.7 ± 0.2	1.260
46	0.75 ± 0.06	0.82 ± 0.03	15.0 ± 1.0	± 0.34 ± 0.06	3.8 ± 0.7	1.272
62	0.73 ± 0.07	1.00 ± 0.36	14.5 ± 0.6	∓ 0.35 ± 0.06	4.2 ± 0.4	0.822

[a] For this angular-momentum window a slightly worse fit has been obtained with $\beta = +0.20$.

Table 2
The temperature for GDR decay in the first step, the temperature averaged over all decay steps and the angular frequency for each of the three angular-momentum windows. The resulting equilibrium deformation and the average deformation obtained from calculations as described in ref. [8] are listed.

$\langle J \rangle$ ($\hbar$)	T_{1st} (MeV)	$\langle T \rangle$ [a] (MeV)	$\hbar\omega$ (MeV)	β_{eq}	$\langle \beta \rangle$
32	1.89	1.64	0.45	-0.08	-0.32
46	1.78	1.54	0.63	-0.13	-0.34
62	1.60	1.35	0.80	-0.19	-0.37

[a] The yield of γ-rays at 15 MeV in each step has been used as a weight factor.

the data in fig. 1 for the case $a = A/8$ MeV^{-1}. The GDR parameters deduced from the best fits for this level density parameter are summarized in table 1. The results obtained with $a = A/9$ MeV^{-1} are comparable, only the deduced widths are slightly larger. The value $a = A/8$ MeV^{-1} for the level density parameter has also been used by Stolk et al. [5] who have studied the same system using a comparable set-up but using instead a thick target in which all recoiling compound nuclei were stopped. This may introduce some difference in the measured γ-ray multiplicity and as a consequence in the selected angular-momentum domains.

The resulting parameters have been used to convert the data to absorption cross sections following the procedure described by Gundlach et al. [14]. The resulting spectra are shown in fig. 2. The most interesting results (cf. table 1) are the constant centroid energy $\langle E \rangle$ and the large deformation parameter β, deduced following the procedure described by Danos [21]. The average of the centroid energy deduced from the fits, $\langle E \rangle = = 14.9 \pm 0.5$ MeV, is in excellent agreement with the value $E_{GDR} = 14.7$ MeV (average

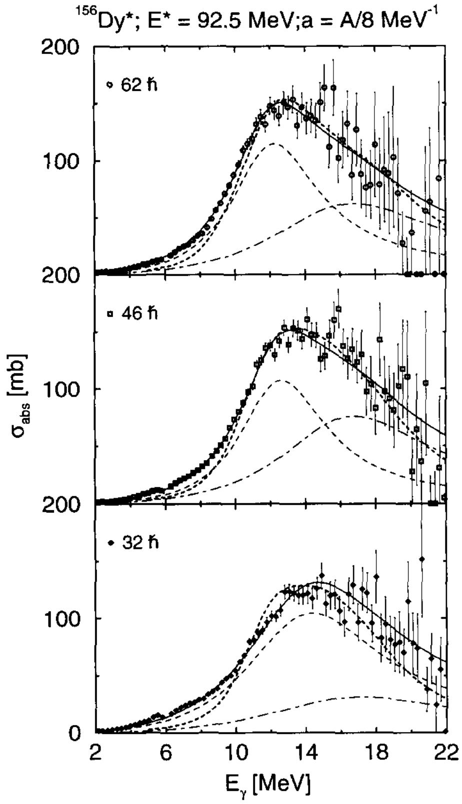

Fig. 2. High-energy γ-ray spectra converted to absorption cross sections. For each angular-momentum window also the result of the fit using CASCADE (solid curve), separated into its two components (long-dashed curve and dash-dotted curve), and the results of theoretical calculations (short-dashed curve) as discussed in the text, are shown.

for ^{148}Sm and ^{150}Sm) obtained from the systematics of the GDR built on the ground state. This result is consistent with that of the study of Stolk et al. [5]. However, no clear indication of a shape transition from prolate to oblate, when the angular momentum increases from $\langle J \rangle = 32\hbar$ to $\langle J \rangle = 62\hbar$, could be obtained as suggested in ref. [5].

Using the Landau theory of shape transitions, the Landau free energies $F(T, \omega, \beta, \gamma)$ have been calculated for the three angular-momentum windows. The used temperatures $\langle T \rangle$, listed in table 2, were ob-

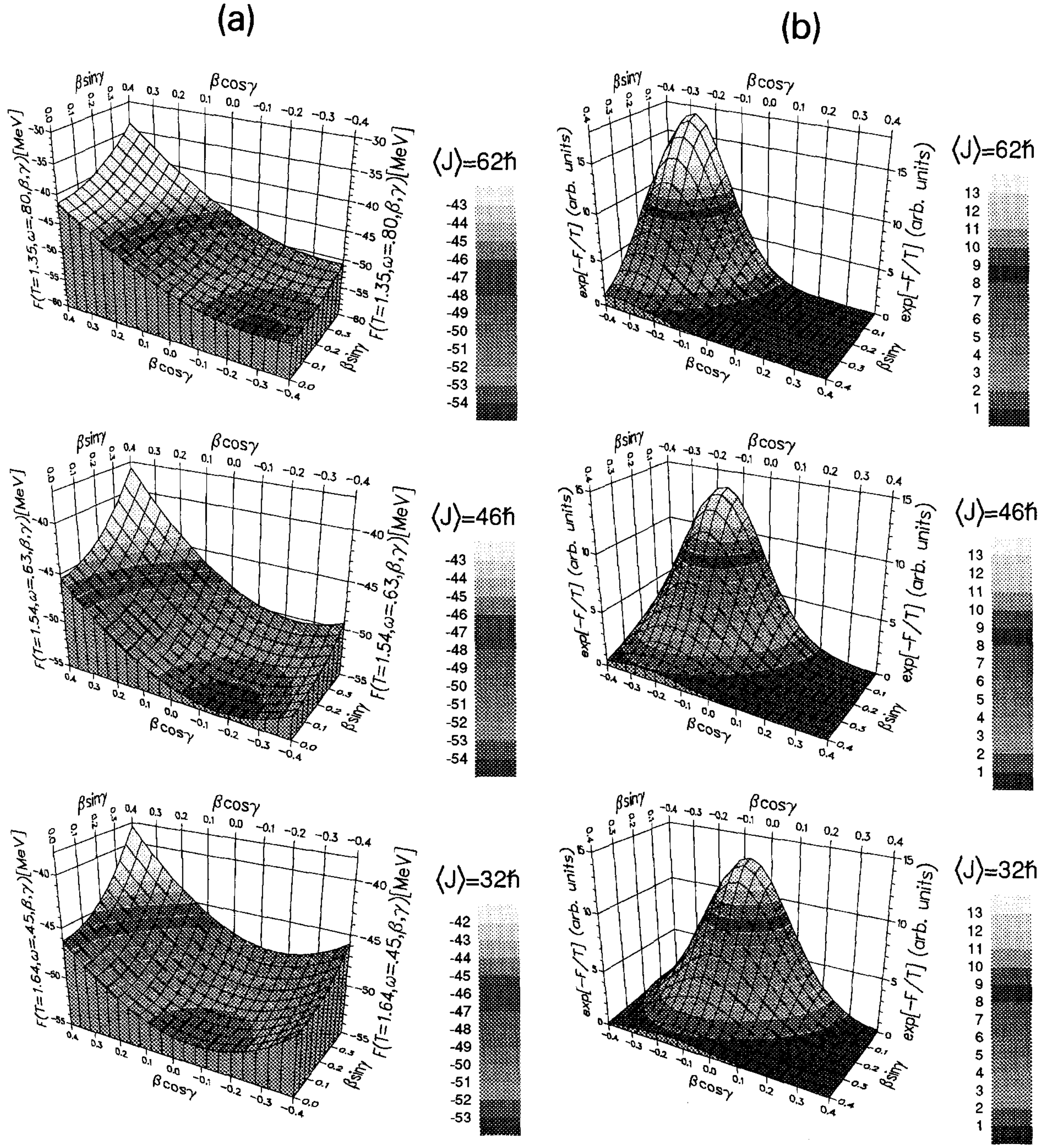

Fig. 3. (a) The Landau free-energy surfaces $F(T, \omega, \beta, \gamma)$ and (b) the corresponding Boltzmann factors $\exp(-F/T)$ for $\langle J \rangle = 32\hbar$ (bottom), $46\hbar$ (middle) and $62\hbar$ (top). For reasons of presentation the graphs in (b) have been rotated by 180° around the z-axis. Notice that in order to evaluate $\langle \beta \rangle$, the metric $\beta^4 |\sin 3\gamma|$ has to be taken into account in addition to the Boltzmann factor.

tained by performing a weighted averaging over all decay steps. The angular frequencies ω corresponding to the different values of $\langle J \rangle$, are also listed in table 2. The equipotential surfaces for $F(T, \omega, \beta, \gamma)$ are shown in fig. 3a with the corresponding Boltzmann weight factor $\exp[-F(T, \omega, \beta, \gamma)/T]$ shown in fig. 3b. The equilibrium deformations corresponding to the minimum in each of the potential energy surfaces are $\beta_{eq}=0.08$, 0.13 and 0.19 and all correspond to an oblate non-collective shape.

The short-dashed curves shown in fig. 2 are the calculated GDR absorption cross sections using the method described in ref. [8]. The centroid energy and width taken in the calculations are $E_0=14.61$ MeV and $\Gamma_0=3.96$ MeV. These parameters are usually determined from the GDR built on the ground state. Since no ground-state GDR measurements exist for ^{156}Dy, these were obtained through interpolation of the values of neighbouring nuclei. The resulting GDR absorption cross section is obtained by averaging over the free-energy surfaces in fig. 3a using the unitary metric $\beta^4|\sin 3\gamma|\ d\beta\, d\gamma\, d\Omega$ and the Boltzmann factor $\exp[-F(T, \omega, \beta, \gamma)/T]$.

Considering that the calculations have no free parameters, the agreement between the data and these calculations is very good as can be seen from fig. 2, in which the calculations have been multiplied by a factor 0.8. The experimentally observed GDR strength distributions for the three angular-momentum domains are nicely reproduced by the calculations. The weighted averages for the deformation (see table 2) $\langle \beta \rangle = 0.32$, 0.34 and 0.37 for $\langle J \rangle = 32\hbar$, $46\hbar$ and $62\hbar$, respectively, also agree well with the deformations obtained from the statistical model fits. This result shows the dominant role of shape fluctuations causing much larger widths than those measured for the GDR built on the ground state. The calculated widths only slightly underestimate the experimental widths (see fig. 2). The disagreement is a bit worse for the angular-momentum window with $\langle J \rangle = 32\hbar$. The agreement will certainly improve if the calculations, performed at one temperature and at one specific value for the angular velocity for each angular-momentum domain, were averaged over the actual distribution of temperatures and angular momenta. Although such a procedure is in principle possible, it can only be performed for spectra that correspond to a narrow range in angular momentum and temperature because many time-consuming microscopic calculations are required to determine the free-energy surfaces.

It is of interest to note that the data indicate large widths for the GDR strength distribution and do not show any indication for motional narrowing. Due to these large widths, there are only small differences in the GDR strength distributions for an oblate and a prolate nucleus at a given deformation parameter β. Therefore the shape transitions suggested in refs. [4,5] have to be taken with some caution. For example, it appeared that even the data taken for the lowest angular-momentum window in the present study can be reasonably well fitted with a strength distribution for a prolate deformed nucleus with $\beta=0.20$ (see table 1).

In conclusion, the angular-momentum dependence of the GDR in ^{156}Dy has been studied at three different angular-momentum domains and at finite intermediate temperatures. The observed GDR strength distributions are nicely reproduced by calculations in which statistical shape fluctuations around an oblate equilibrium shape, the deformation of which increases with spin, are taken into account. Possible changes in the equilibrium deformation β_{eq} are masked by the shape fluctuations leading to a much more constant and large average deformation $\langle \beta \rangle \sim 0.35$ in good agreement with experiment.

References

[1] J.J. Gaardhøje, Ann. Rev. Nucl. Part. Sci. 47 (1992) 483, and references therein.
[2] P. Thirolf et al., Nucl. Phys. A 482 (1988) 93c.
[3] R.F. Noorman et al., Phys. Lett. B 292 (1992) 257.
[4] A.M. Bruce et al., Phys. Lett. B 125 (1988) 237.
[5] A. Stolk et al., Phys. Rev. C 40 (1989) R2454.
[6] Y. Alhassid, S. Levit and J. Zingman, Phys. Rev. Lett. 57 (1986) 539.
[7] Y. Alhassid, J. Zingman and S. Levit, Nucl. Phys. A 496 (1987) 205.
[8] Y. Alhassid and B. Bush, Nucl. Phys. A 509 (1990) 461.
[9] R.A. Broglia et al., Phys. Rev. Lett. 58 (1987) 326.
[10] W.E. Ormand et al., Phys. Rev. Lett. 69 (1992) 2905.
[11] J.J. Gaardhøje et al., Phys. Rev. Lett. 53 (1984) 148.
[12] C.A. Gossett et al., Phys. Rev. Lett. 54 (1985) 1486.
[13] Y. Alhassid, B. Bush and S. Levit, Phys. Rev. Lett. 61 (1988) 1926.
[14] J.J. Gundlach et al., Phys. Rev. Lett. 65 (1990) 2523.
[15] Y. Alhassid and B. Bush, Phys. Rev. Lett. 65 (1990) 2527.